National Aeronautics and Space Administration

Small Launch Vehicle (SLV) Concept Development for Affordable Multi-Stage Inline Configurations

May 22, 2014

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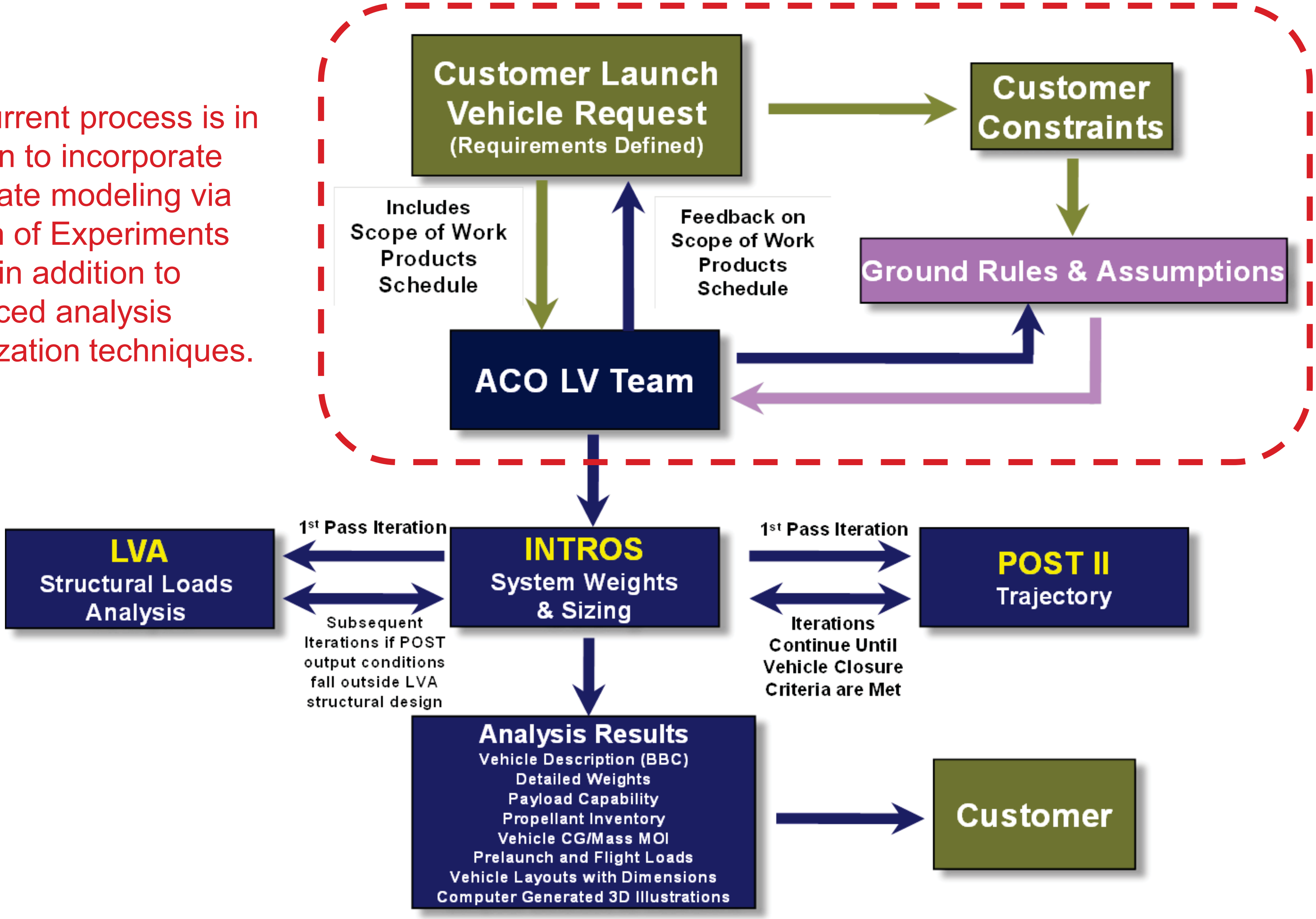
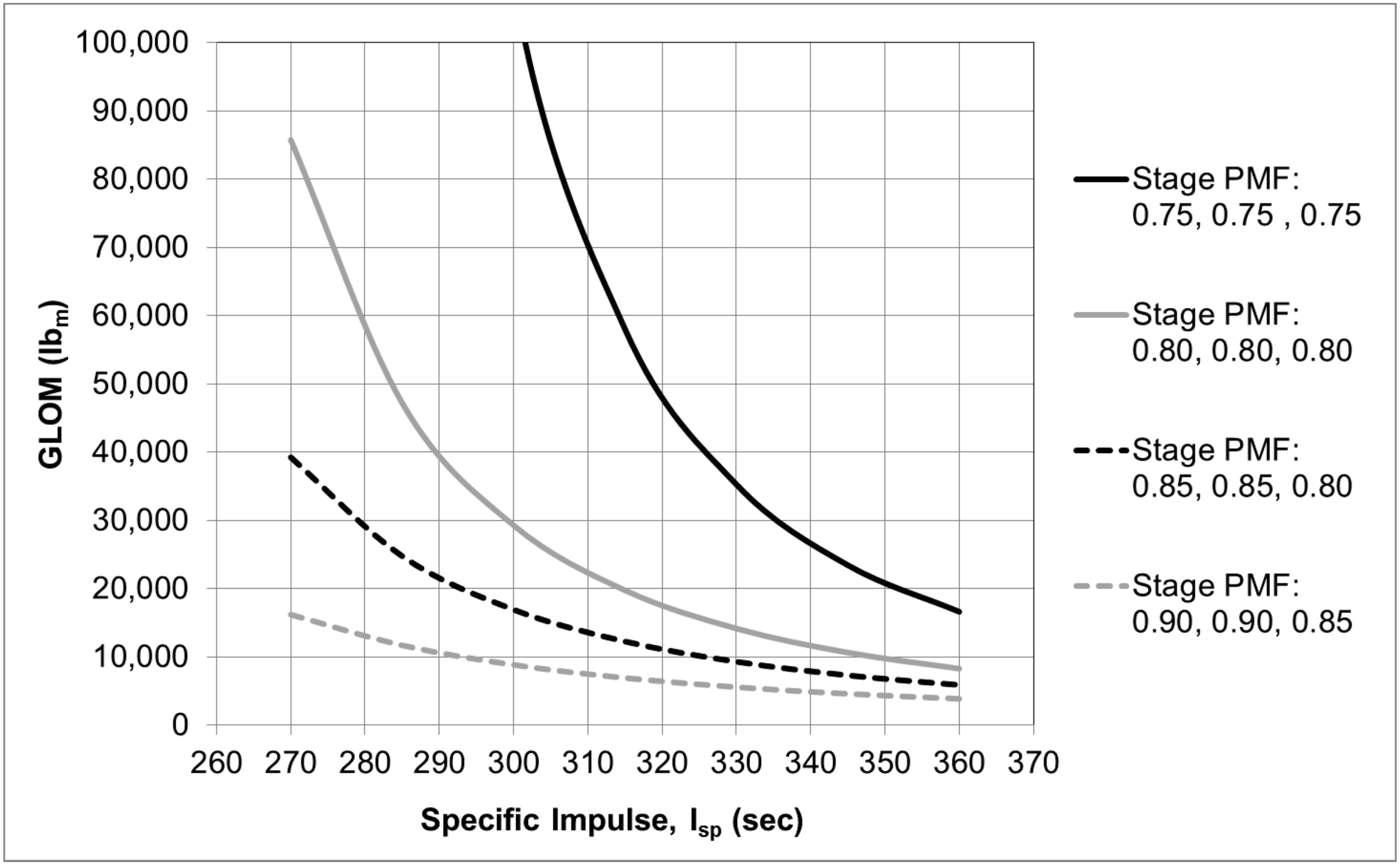
MSFC Advanced Concepts

Earth-To-Orbit Team Process

The current process is in revision to incorporate surrogate modeling via Design of Experiments (DoE) in addition to enhanced analysis visualization techniques.



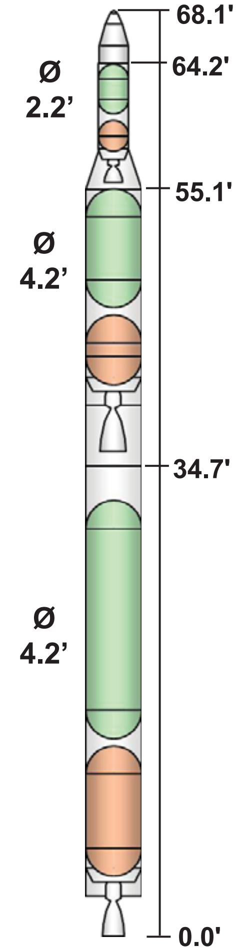
Generic Trade Space Sizing Tool



NESC-1 Ground Rules & Assumptions

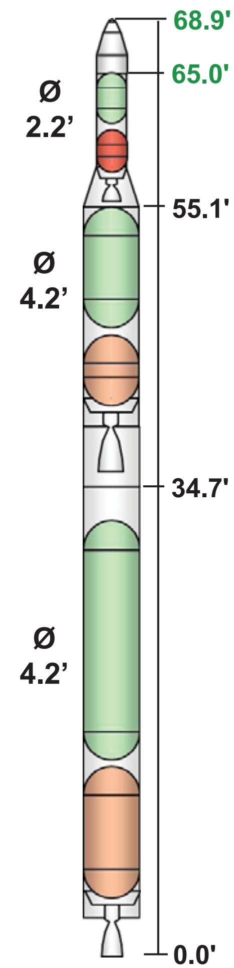
Item	Stage 1	Stage 2	Stage 3
Propulsion			
Propellants	LOX / RP-1	LOX / RP-1	LOX / RP-1
Mixture ratio, MR	2.77	2.77	2.77
Vacuum Thrust (lb_f)	55,000	18,000	1,000
Vacuum Specific impulse, I_{sp} (sec)	300	300	300
Propellant feed system type	Pressure-fed	Pressure-fed	Pressure-fed
Propellant tank pressures (psia)	550	550	250
Structures			
Stage diameter (ft)	4.17	4.17	2.17
Safety factor	1.4	1.4	1.4
Mass growth allowance, MGA (%)	batt, avionics = 25 all other = 18	batt, avionics = 25 all other = 18	batt, avionics = 25 all other = 18
All vehicle structural material	IM7/877	IM7/877	IM7/877
Trajectory			
Orbit type / delivery altitude (nmi)	Circular / 200		
Inclination (deg)	28.5°		

Propellant Mass Fraction (PMF) 0.84 0.83 0.71

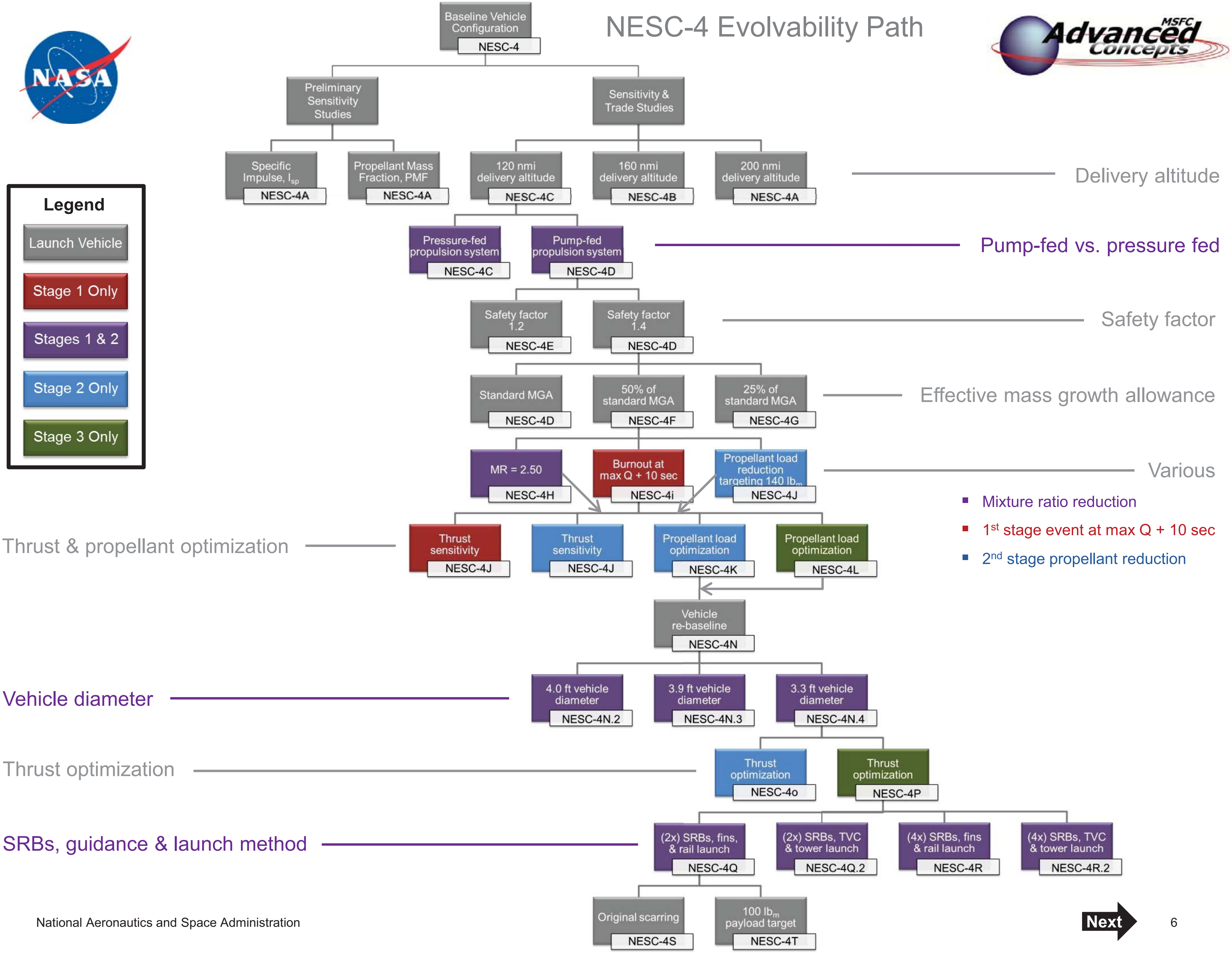


NESC-4 Ground Rules & Assumptions

Item	Stage 1	Stage 2	Stage 3
Propulsion			
Propellants	LOX / RP-1	LOX / RP-1	LOX / LCH_4
Mixture ratio, MR	2.77	2.77	3.45
Vacuum Thrust (lb_f)	55,000	18,000	1,000
Vacuum Specific impulse, I_{sp} (sec)	300	300	360
Propellant feed system type	Pressure-fed	Pressure-fed	Pressure-fed
Propellant tank pressures (psia)	550	550	250
Structures			
Stage diameter (ft)	4.17	4.17	2.17
Safety factor	1.4	1.4	1.4
Mass growth allowance, MGA (%)	batt, avionics = 25 all other = 18	batt, avionics = 25 all other = 18	batt, avionics = 25 all other = 18
All vehicle structural material	IM7/877	IM7/877	IM7/877
Trajectory			
Orbit type / delivery altitude (nmi)	Circular / 200		
Inclination (deg)	28.5°		
Propellant Mass Fraction (PMF)	0.84	0.83	0.67

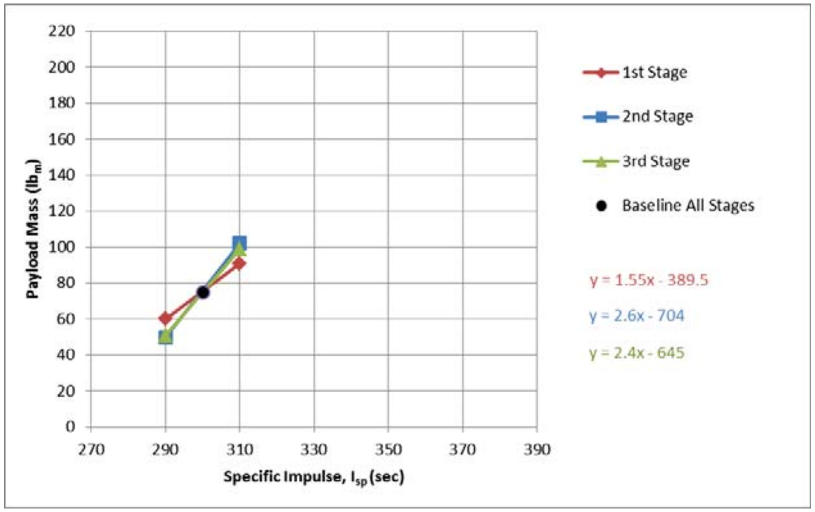


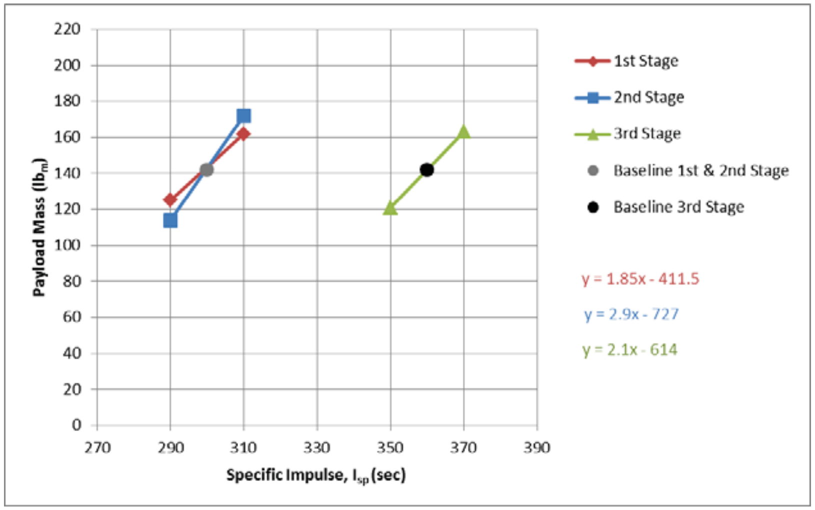
NESC-4 Evolvability Path



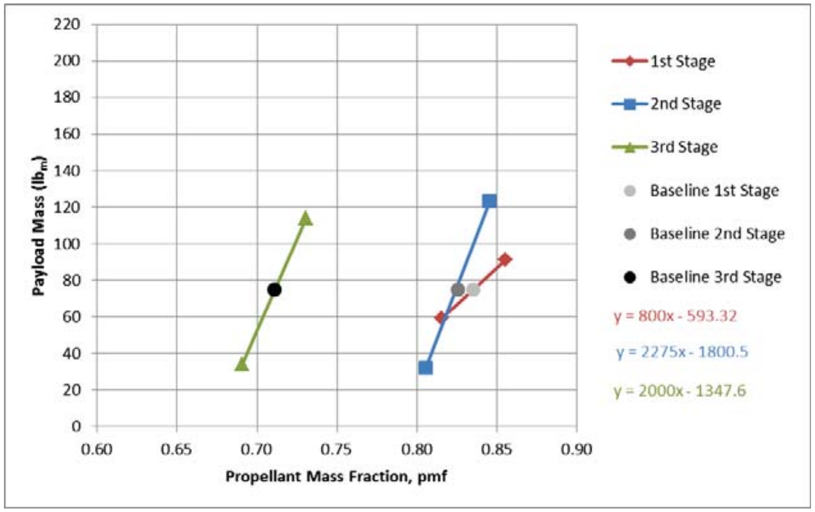
Preliminary Sensitivity Study Results

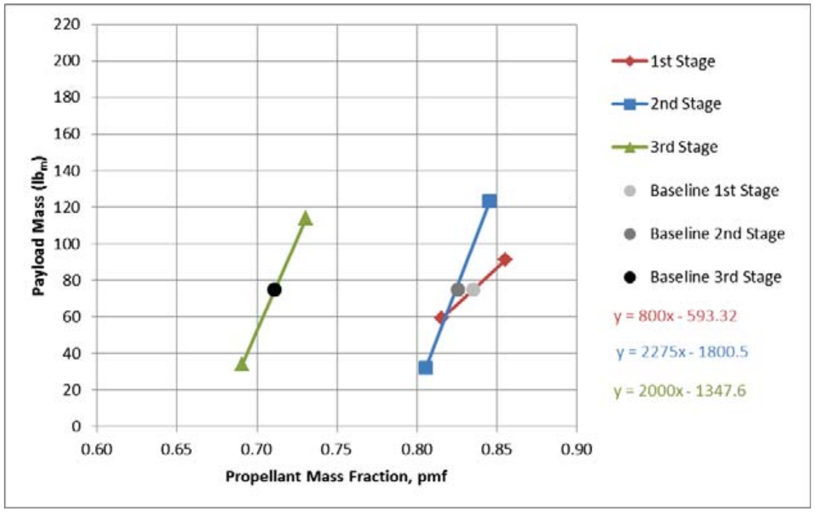
Specific Impulse (I_{sp}) Sensitivity





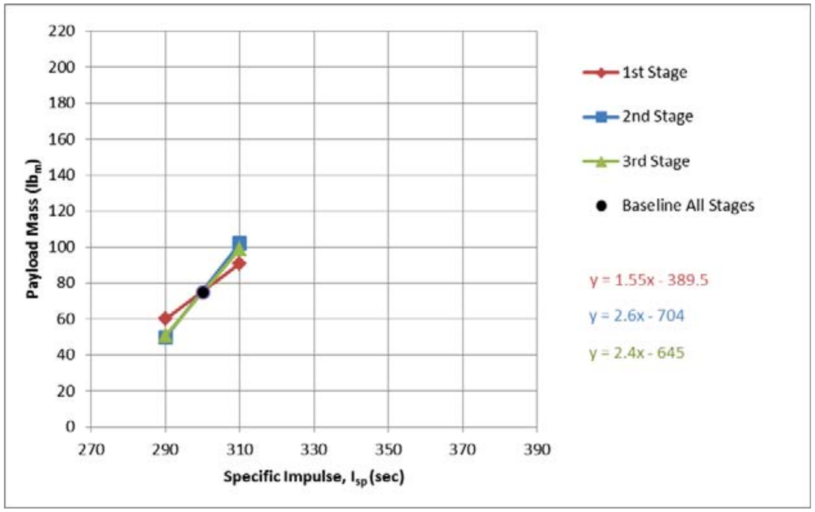
Propellant Mass Fraction (PMF) Sensitivity

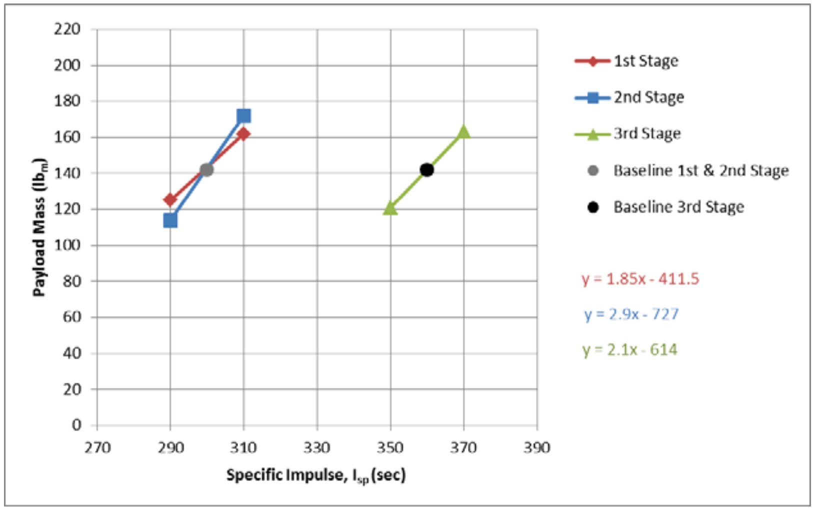




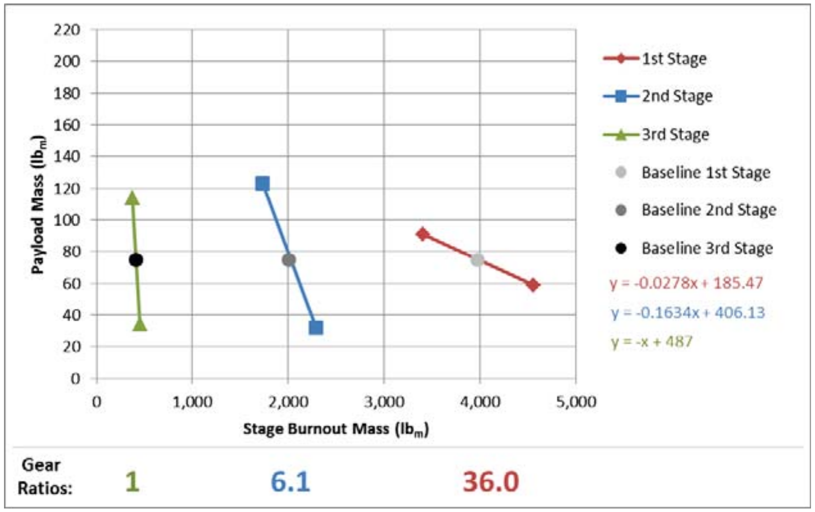
Preliminary Sensitivity Study Results

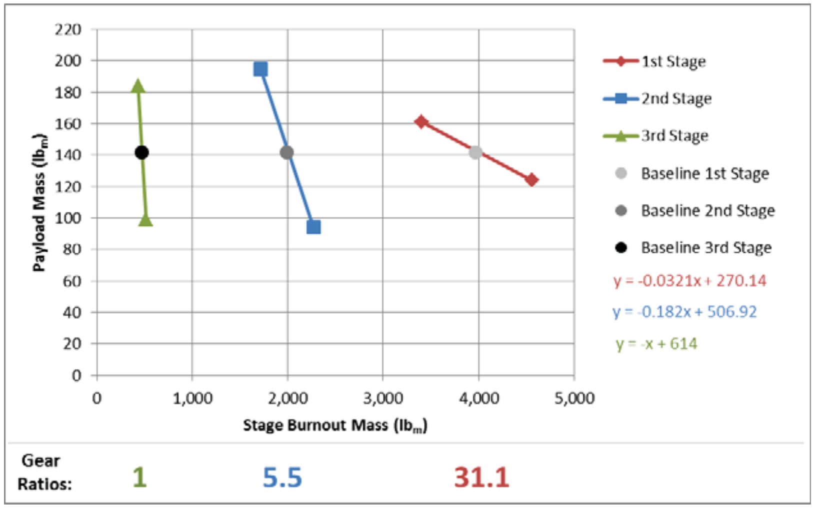
Specific Impulse (I_{sp}) Sensitivity



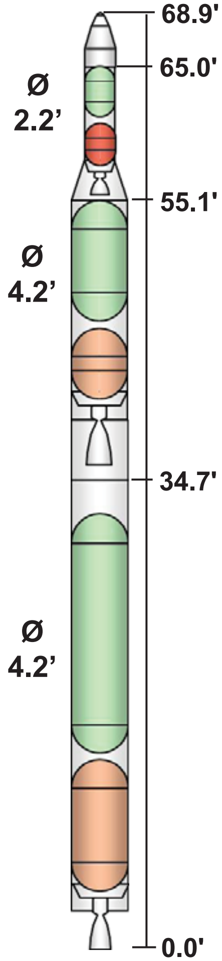


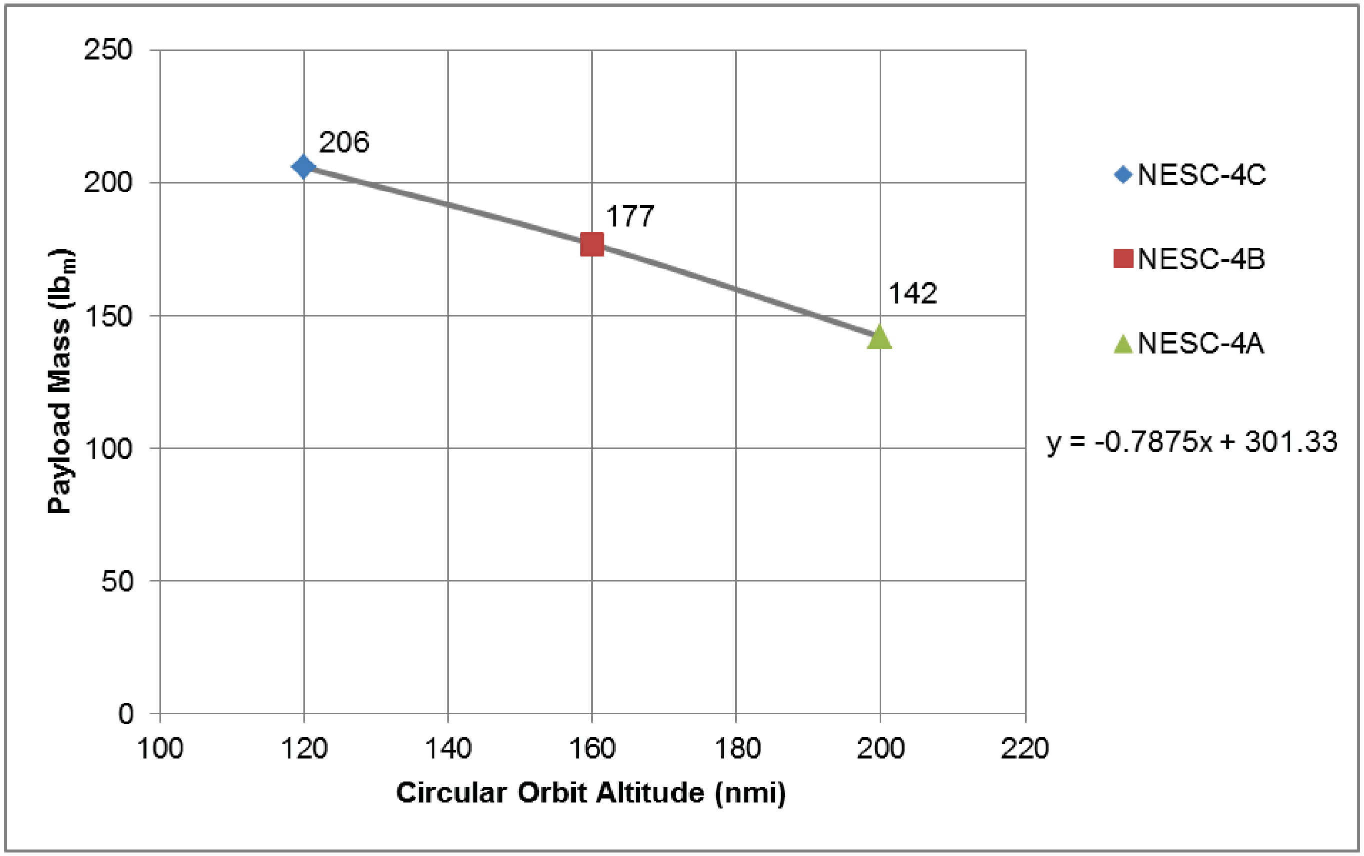
Stage Burnout Mass Sensitivity





Delivery Altitude Sensitivity Study



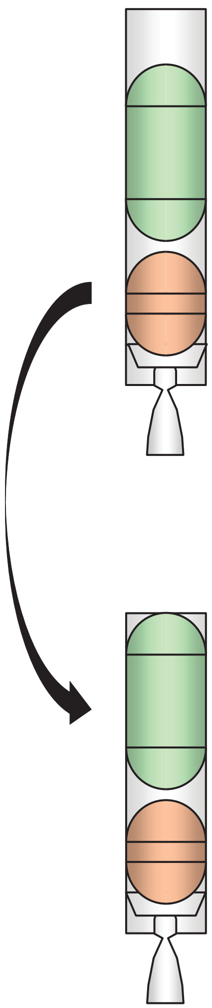


Key information:

- All vehicles configurations were identical but were flown to different altitudes

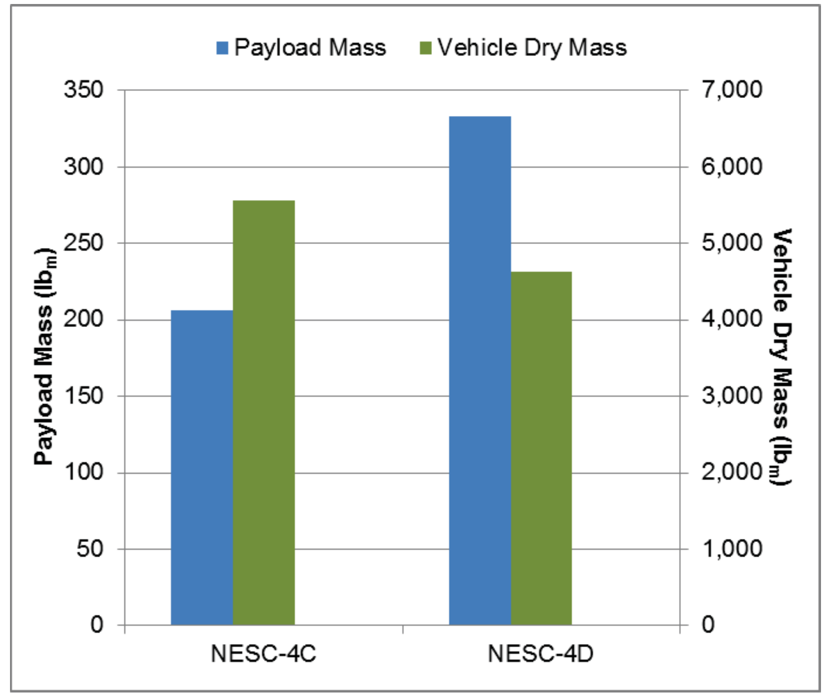
1st / 2nd Stage Propulsion System Trade Study

NESC-4C



Pressure-fed system:

- 550 psia tank pressures
- Thick-walled propellant feed system line
- Larger Helium pressurant volume accommodations in forward skirt

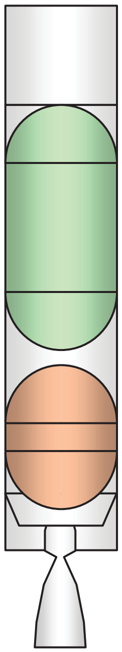


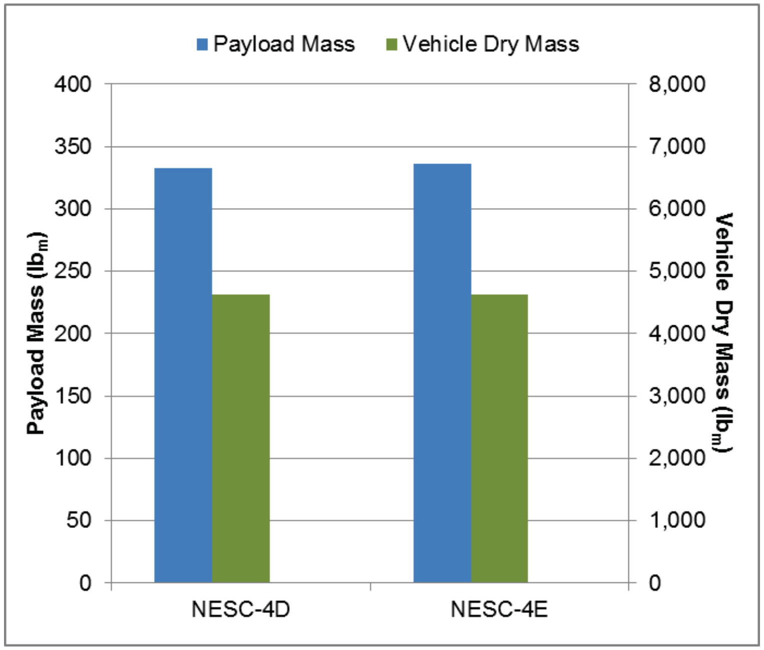
Pump-fed system:

- 50 psia tank pressures
- Thin-walled propellant feed system line
- Smaller Helium pressurant volume accommodations in forward skirt

NESC-4D

Vehicle Safety Factor Sensitivity Study





SF = 1.2 1.4

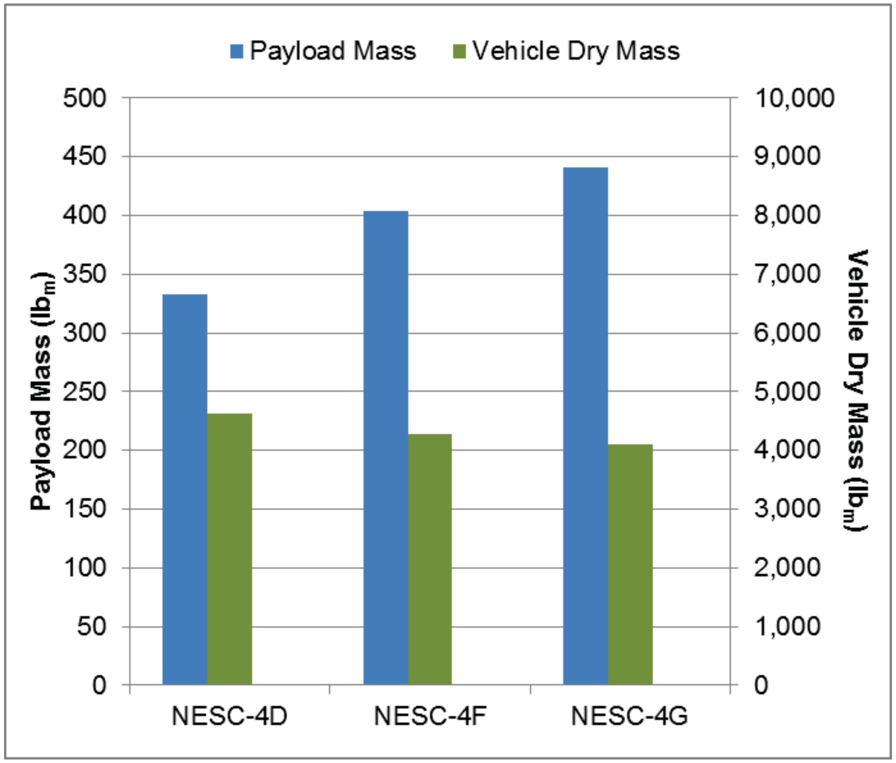
Key Information:

- IM7/877 graphite epoxy composite ($\rho = 0.065\ lb_m/in^3$)
- 0.036 in. minimum gauge wall thickness
- 0.65 structural buckling knockdown factor
- 3σ dispersion placed on angle of attack (α) calculated by POST
- Combined worst case loading
- 1% risk of exceeding peak prelaunch wind loads at KSC

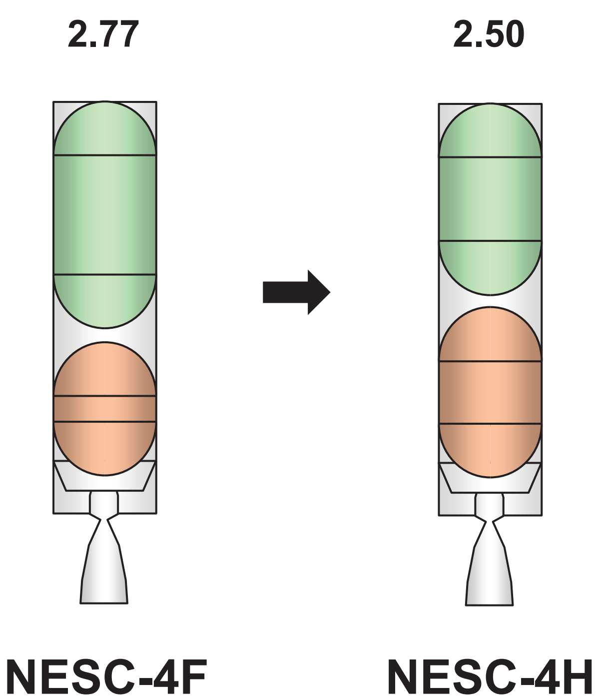
Vehicle MGA Sensitivity Study

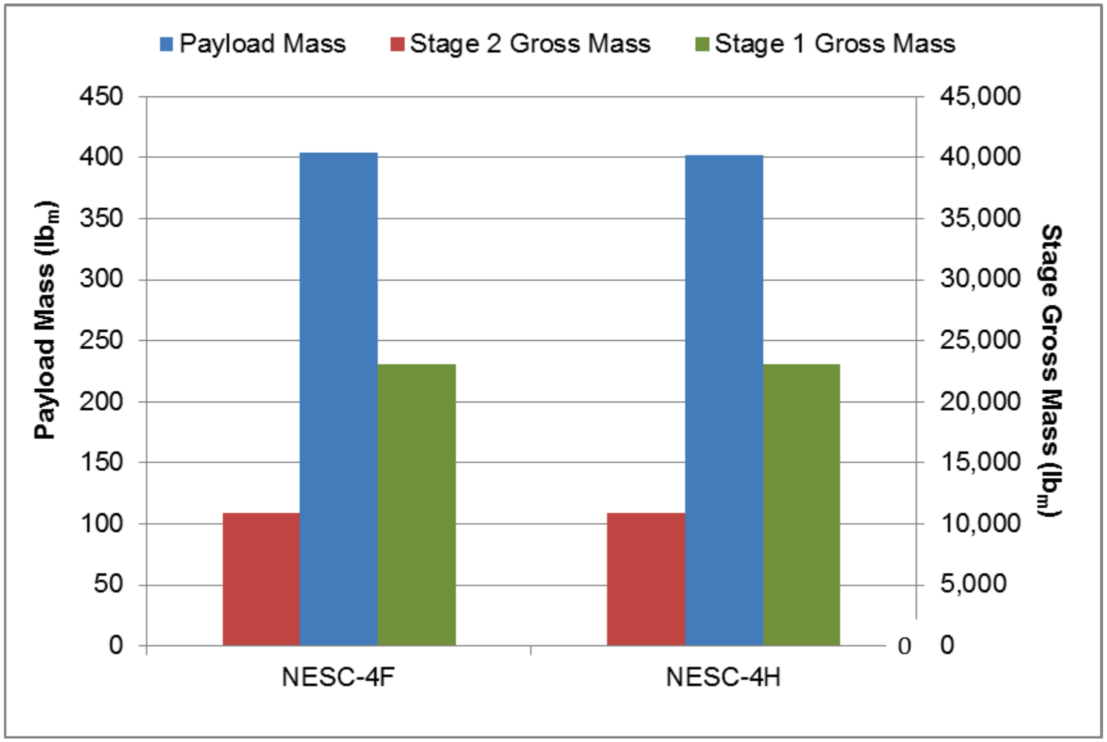
LLV Standard

	NESC-4D	NESC-4F	NESC-4G
Avionics & batteries	25%	12.5%	6.25%
All other components	18%	9%	4.5%
Mass savings	N/A	290 lb_m	430 lb_m



1st / 2nd Stage Mixture Ratio Sensitivity Study



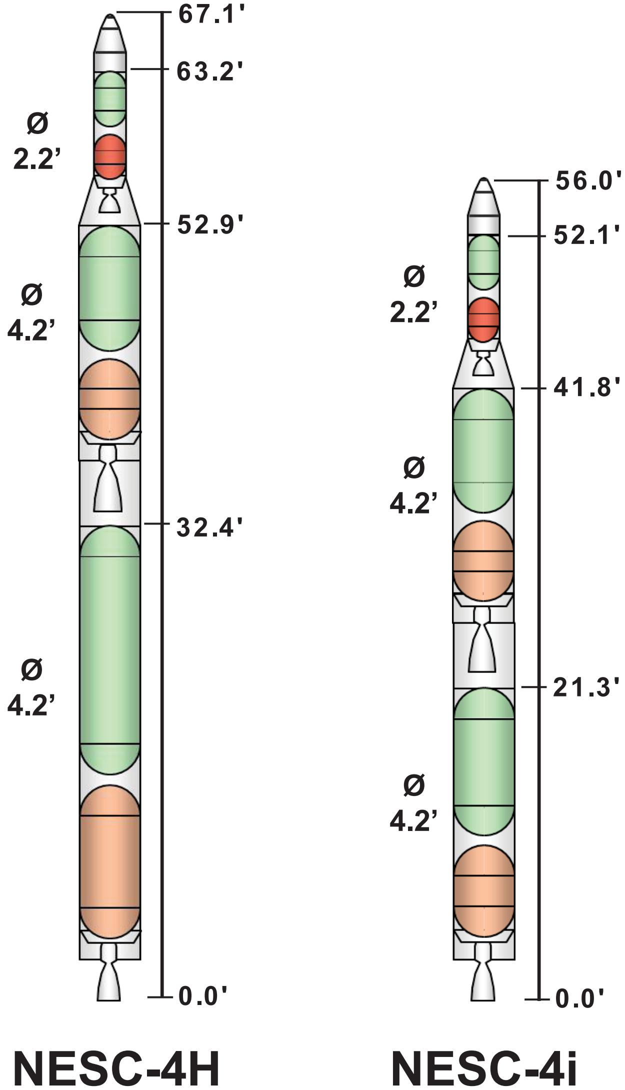


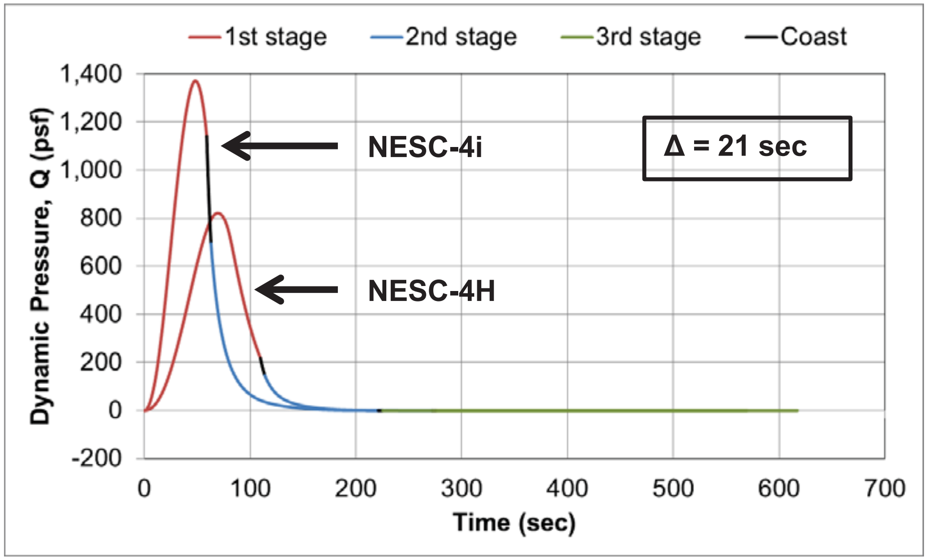
Key information:

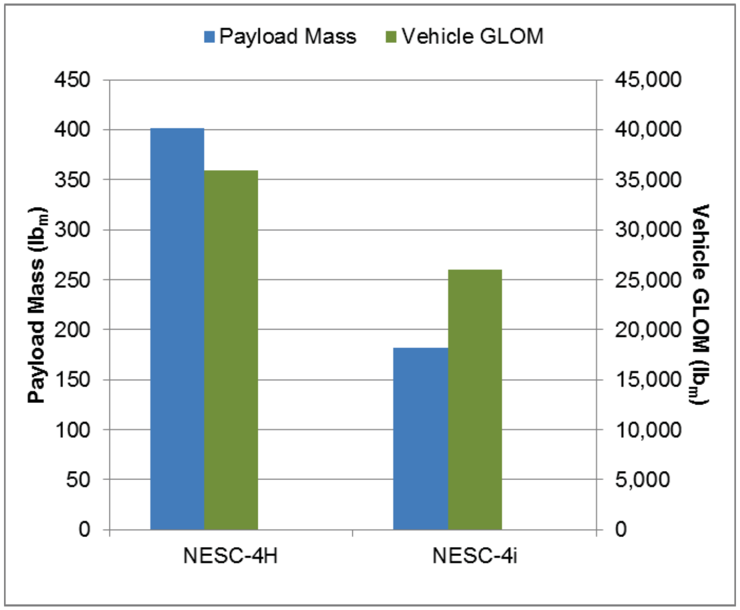
- GLOM was held constant so payload capability was minimally affected.
- MR was adjustable since only conceptual engines were used.

$$\boxed{MR = \frac{\dot{m}_{oxidizer}}{\dot{m}_{fuel}}}$$

Maximum Q Event Sensitivity Study





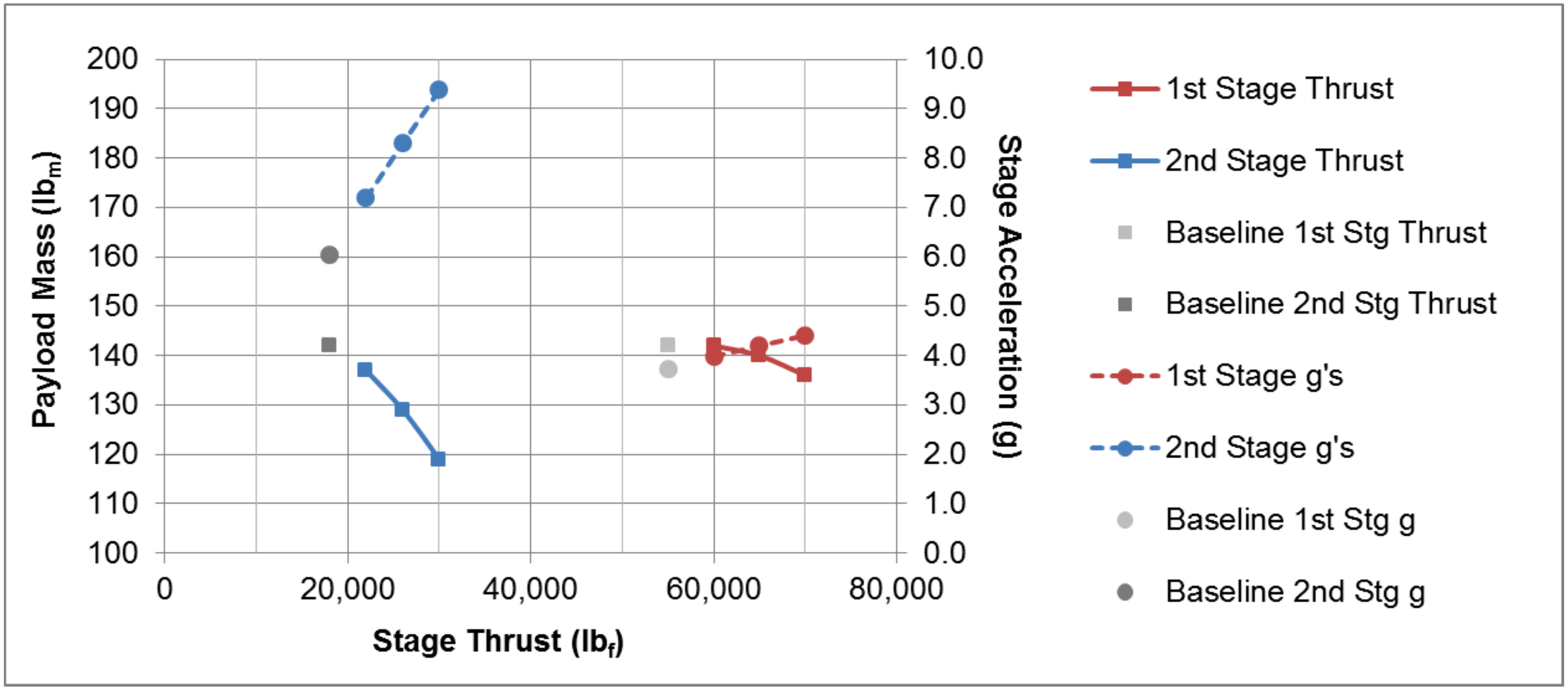


Key information:

- Propellant was removed only from the 1st stage to relocate max Q event in the trajectory.

1st / 2nd Stage Thrust Sensitivity Study

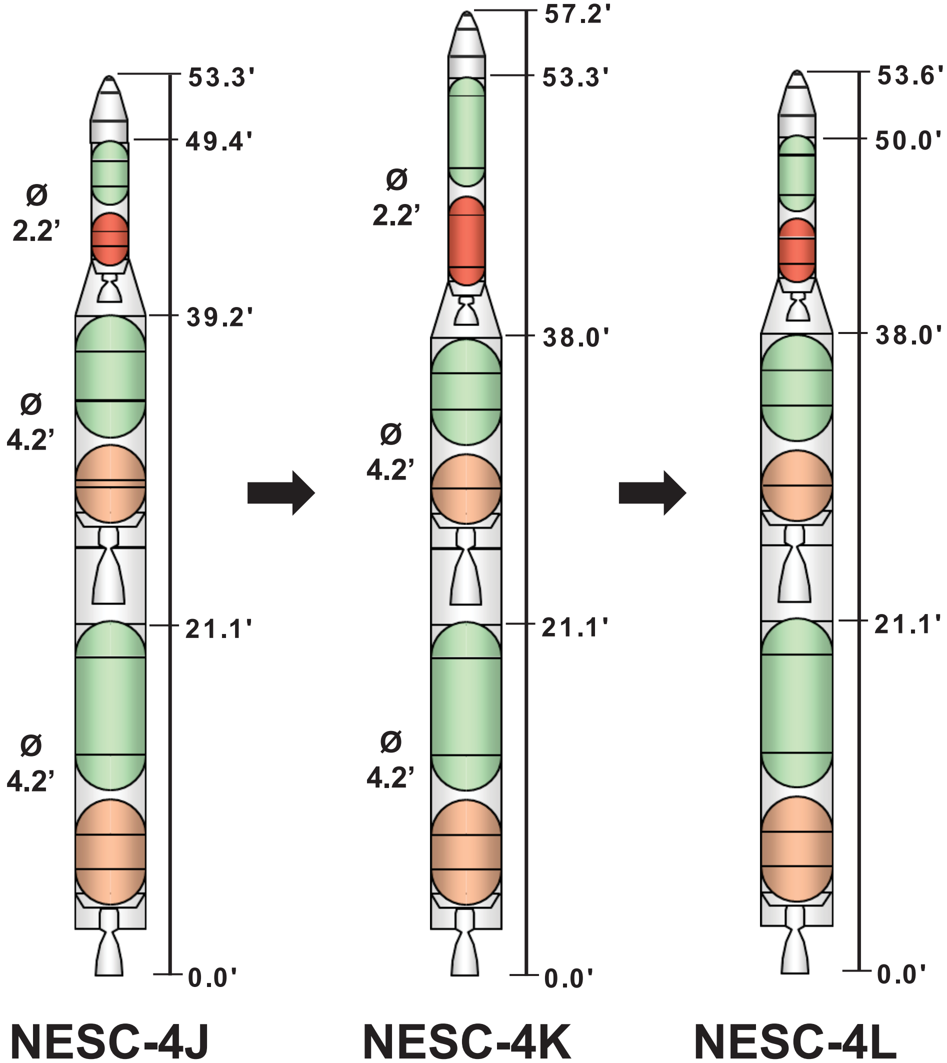
NESC-4J

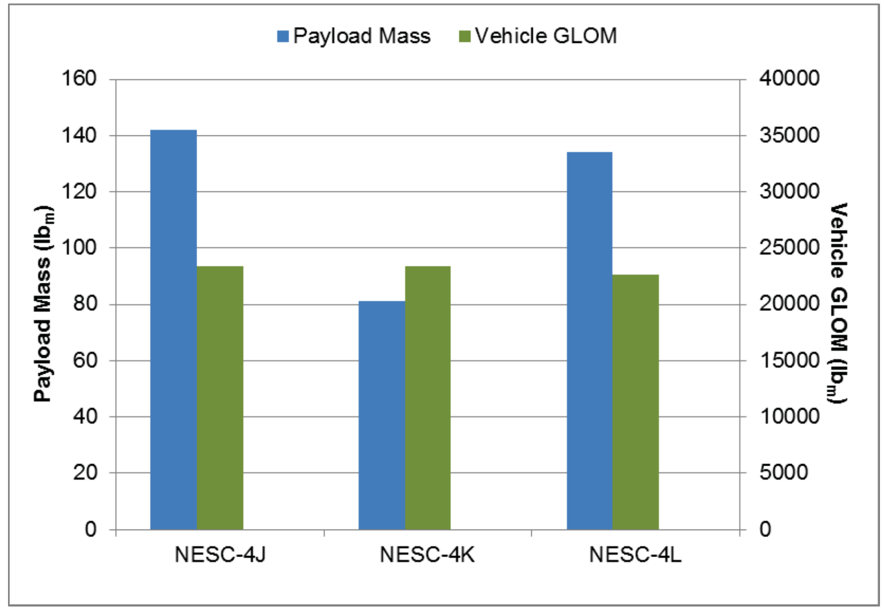


Key information:

- 55,000 lb_f (stage 1) and 18,000 lb_f (stage 2) thrust levels were maintained as result of this sensitivity study.

2^{nd} / 3^{rd} Stage Propellant Load Sensitivity Study





NESC-4K:

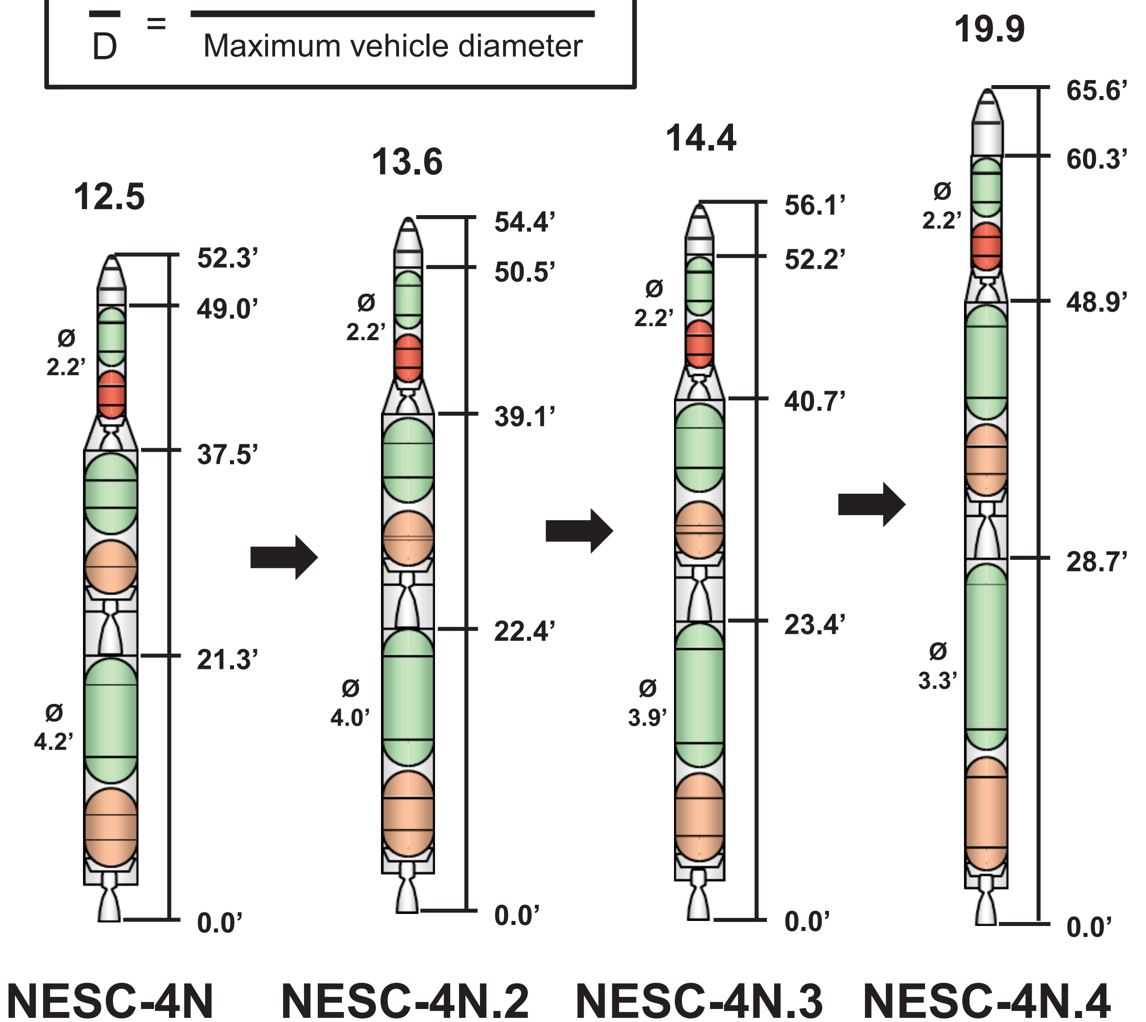
- 2nd stage designed such that RP-1 tank was dome-to-dome.
- Equivalent propellant load was placed in 3^{rd} stage.

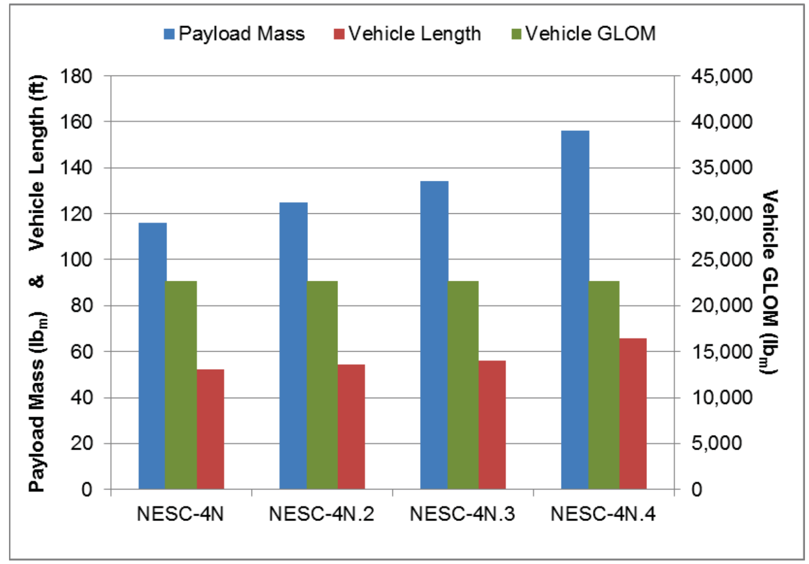
NESC-4J:

- 3^{rd} stage propellant load optimized.

Vehicle Diameter Sensitivity Study

$$\frac{L}{D} = \frac{\text{Total vehicle length}}{\text{Maximum vehicle diameter}}$$

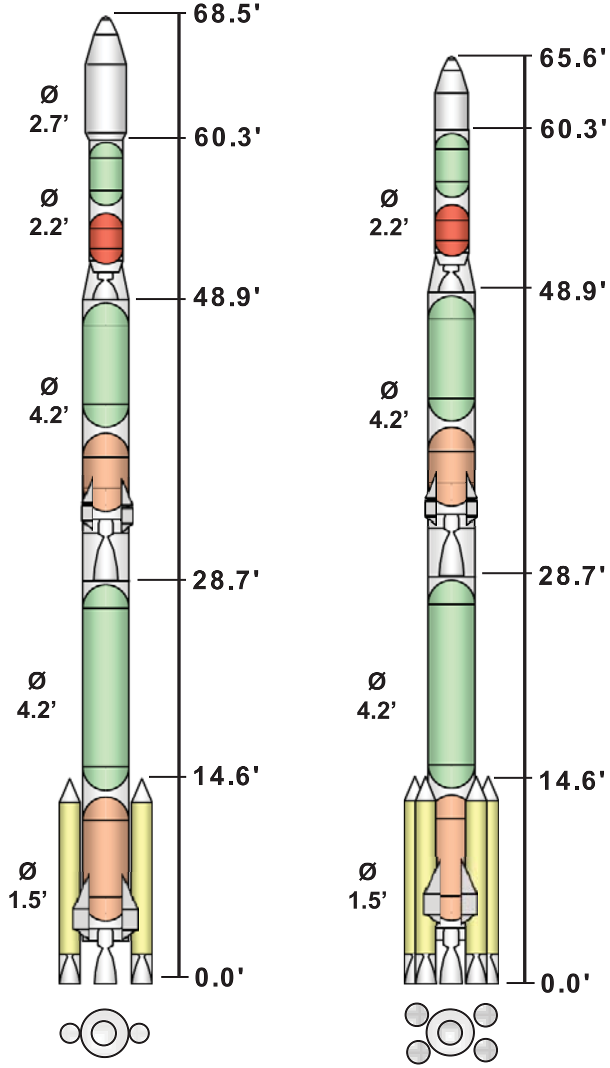




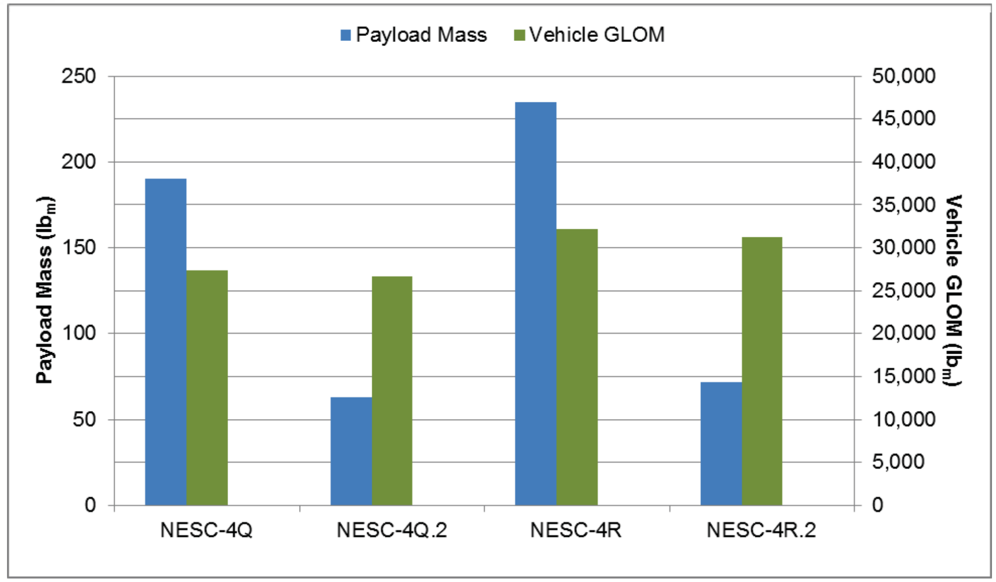
Key information:

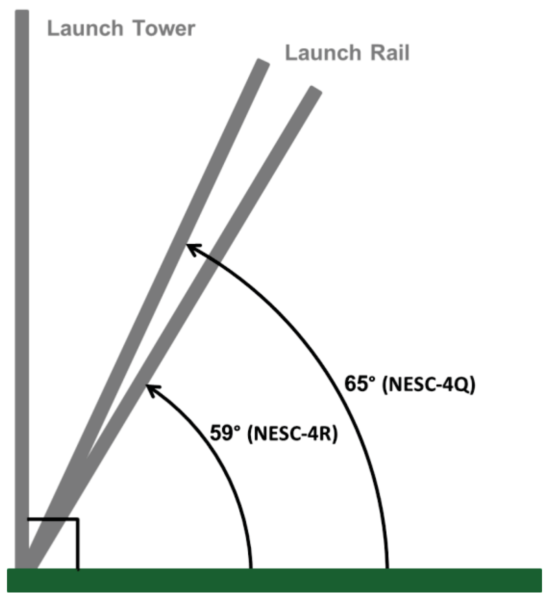
- Vehicle GLOM was maintained such that only stage component geometries were affected.
- Intertank and forward/aft skirts were shortened to accommodate same coverage of propellant tanks as overall dome size shrunk.

SRB & Launch Rail Trade Study



NESC-4Q **NESC-4R**



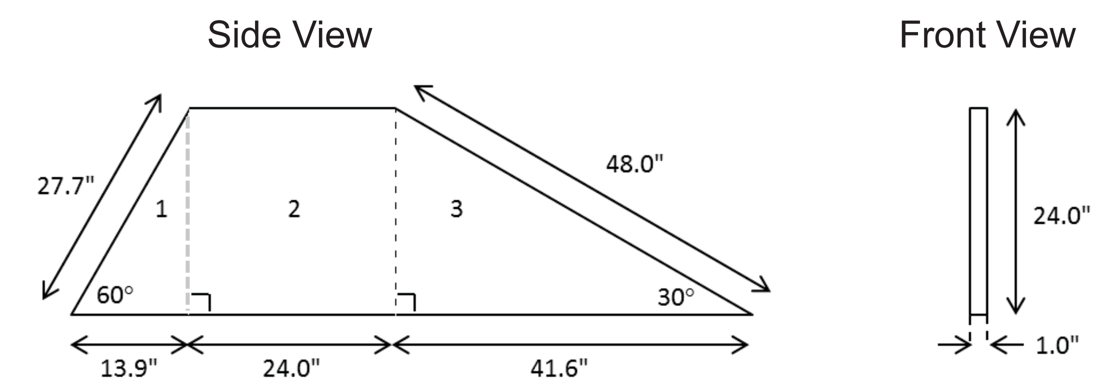


Key information:

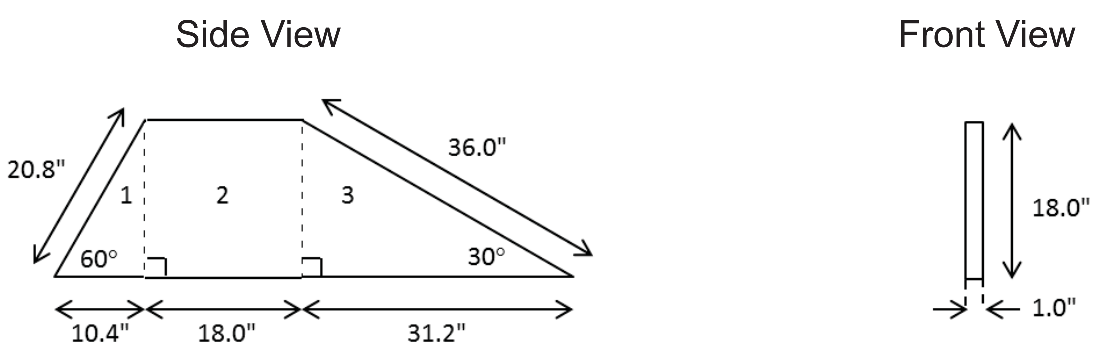
- SRBs (Mk 70 Mod ER) in quantities of 2 and 4 were added to sufficiently increase rail exit velocity.
- 1st and 2nd stage TVC systems were replaced with groups of 4 fins sized to maintain sufficient stability margin.
- Launch configurations were changed from a 90° tower launch to rail launches, each at their own optimized angles.

Passive vs. Active Guidance System

NESC-4Q – 1st stage fin design



NESC-4Q – 2nd stage fin design

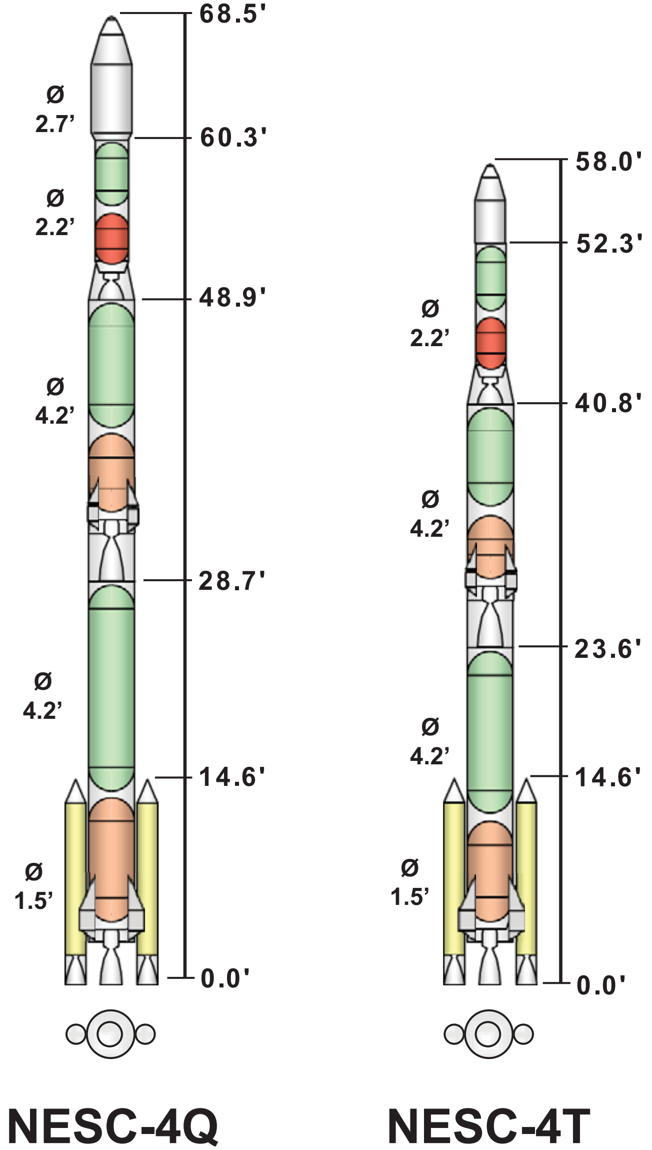


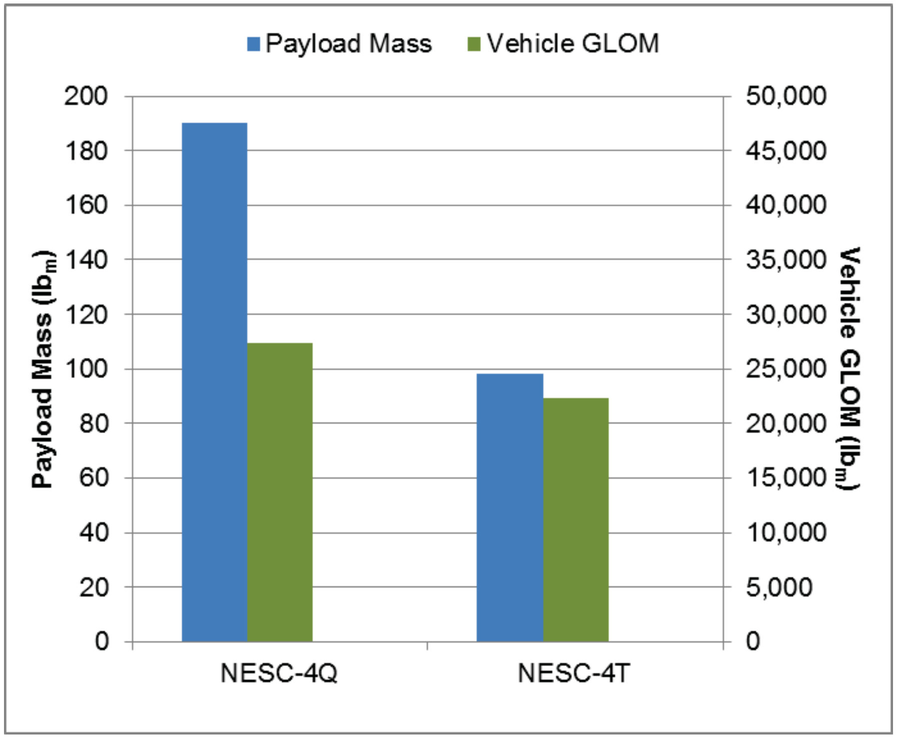
Item	Stage 1	Stage 2
NESC-4Q		
Graphite epoxy composite fins	4	4
Surface area per fin (ft^2)	17.9	10.1
Volume per fin (ft^3)	0.7	0.4
Mass per fin (lb_m)	80.7	45.4
Vehicle stability margin	1.72 (SRBs) 2.13 (no SRBs)	1.21
NESC-4R		
Graphite epoxy composite fins	4	4
Surface area per fin (ft^2)	27.9	10.1
Volume per fin (ft^3)	1.1	0.4
Mass per fin (lb_m)	126.0	45.4
Vehicle stability margin	1.64 (SRBs) 3.09 (no SRBs)	1.25

Note: Stability margin rule of thumb is for CG to be forward of CP at ignition by:

- 1st stage ~ 1.5 – 2.0 vehicle diameters
- Subsequent stages ~ 1.0 vehicle diameters (if low enough in the atmosphere)

100 lb_m Payload Target

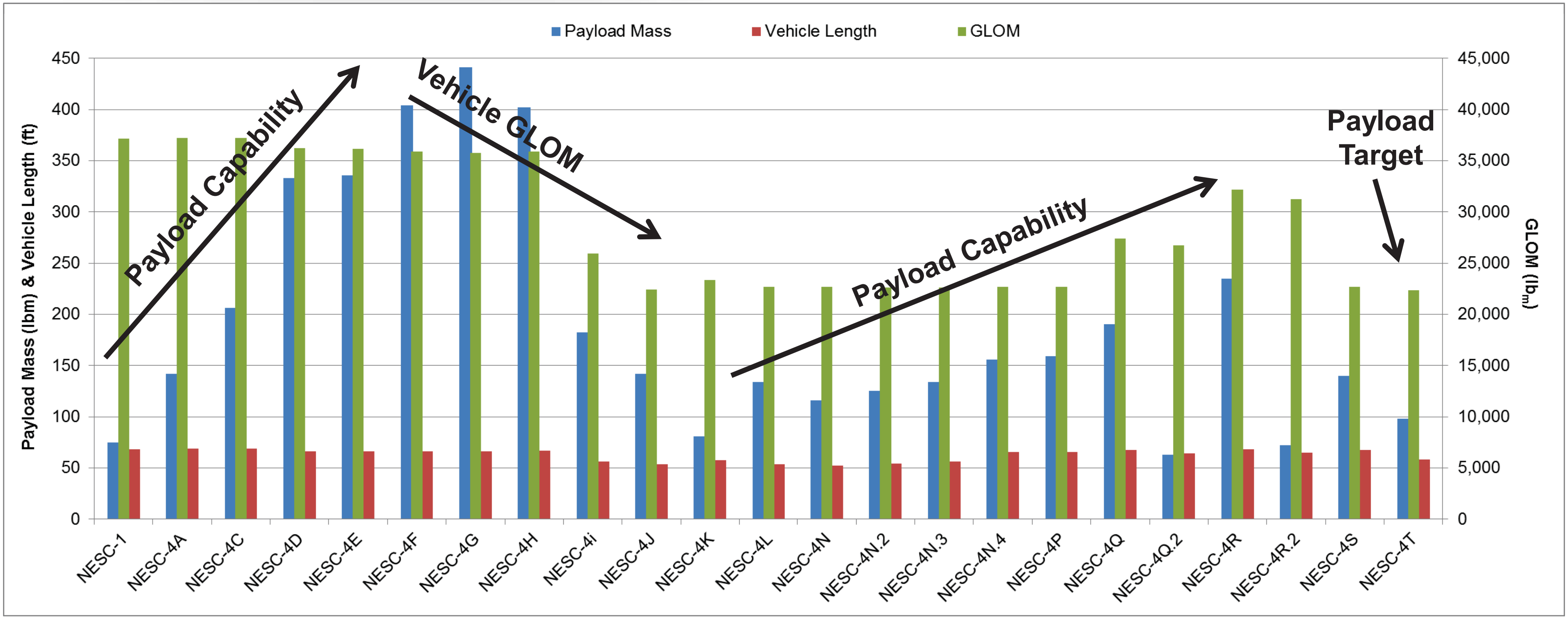




Key Information:

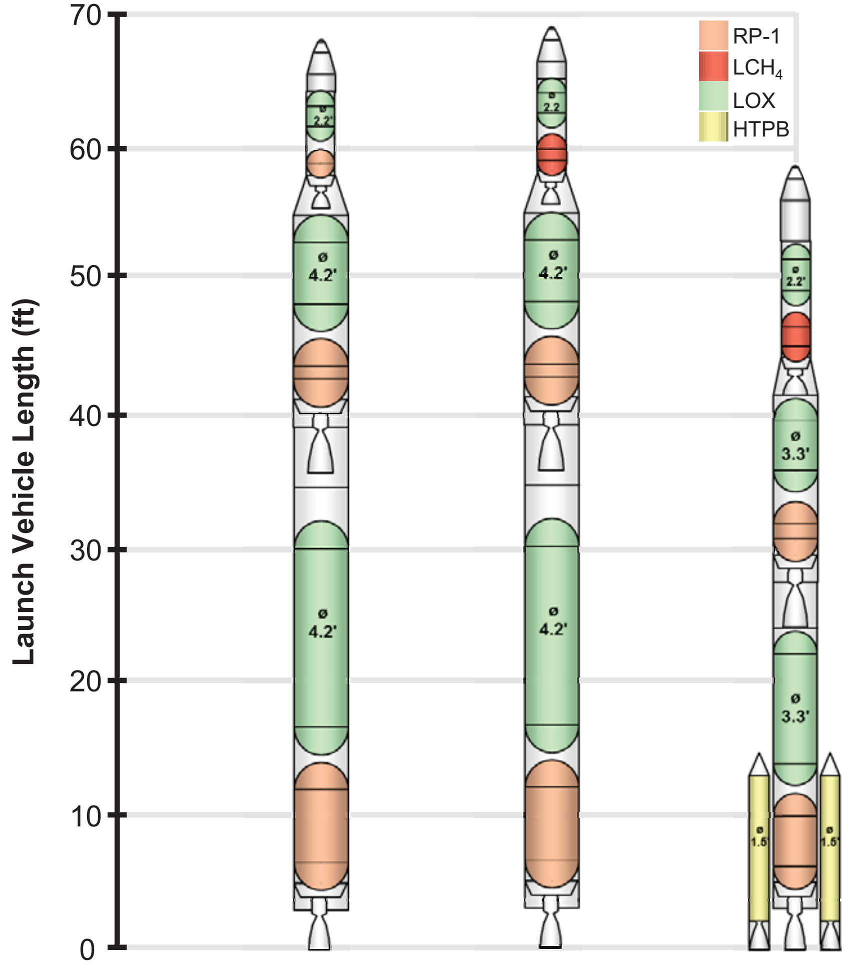
- Removed propellant from both 1st and 2nd stages to achieve 100 lb_m payload target.

Results Summary



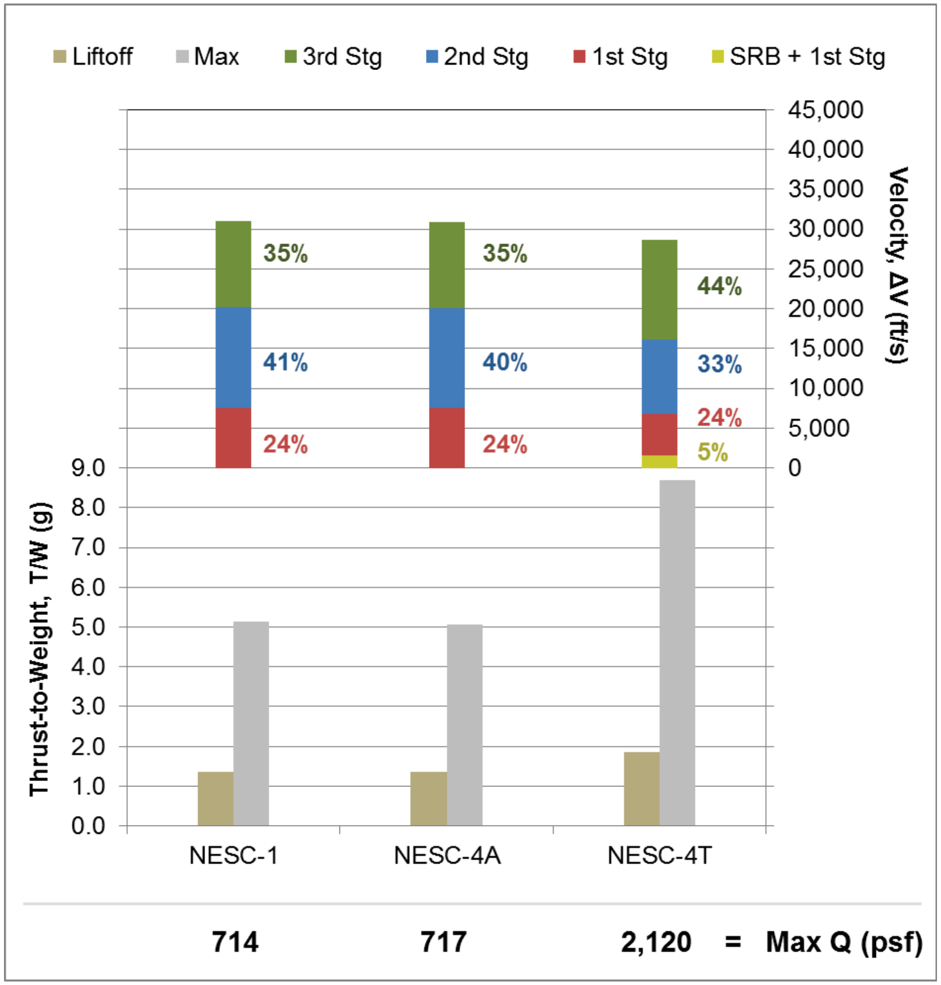
- LOX / RP-1
- 3rd stage LOX / LCH_4
- 120 nmi circ
- 1st/2nd stage pump-fed
- SF = 1.2
- 50% of Standard MGA
- 25% of Standard MGA
- 1st/2nd stage MR = 2.50
- 1st stage max Q + 10
- 140 lb_m payload target
- 2nd stage propellant optimization
- 3rd stage propellant optimization
- MER scrub & rebaseline
- 1st/2nd stage diameter optimization (4.0 ft)
- 1st/2nd stage diameter optimization (3.85 ft)
- 1st/2nd stage diameter optimization (3.3 ft)
- 3rd stage thrust optimization
- (2x) SRBs with 1st/2nd stage fins, rail launc
- (2x) SRBs with 1st/2nd stage TVC, tower launc
- (4x) SRBs with 1st/2nd stage fins, rail launc
- (4x) SRBs with 1st/2nd stage TVC, tower launc
- Original scarring of NESC-4Q.2
- 100 lb_m payload target

Bookend Configuration Comparison



Configuration	NESC-1	NESC-4A	NESC-4T
GLOM (lb_m)	37,133	37,187	22,378
LEO Payload (lb_m)	75	142	98
Delivery Orbit (nmi)	200 circ	200 circ	120 circ

Loads & Ideal Velocity (ΔV) Split Results



BACK-UP

NESC 1 Sensitivity Study Summary

■ = parent vehicle

↓ / ↑ = with reference to parent vehicle

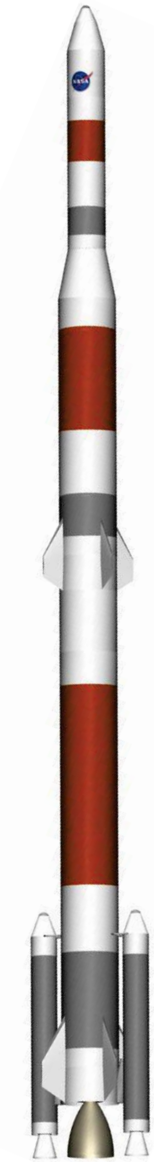
Group	Sensitivity Study	GLOM (lb_m)	Veh. Length (ft)	Payload (lb_m)
NESC-1	Baseline ground rules and assumptions	37,133 –	68.1 –	75 –
NESC-1	1st stage I_{sp} = +10 sec (310 sec)	37,149 ↑	68.1 –	91 ↑
NESC-1	1st stage I_{sp} = -10 sec (290 sec)	37,118 ↓	68.1 –	60 ↓
NESC-1	2nd stage I_{sp} = +10 sec (310 sec)	37,160 ↑	68.1 –	102 ↑
NESC-1	2nd stage I_{sp} = -10 sec (290 sec)	37,108 ↓	68.1 –	50 ↓
NESC-1	3rd stage I_{sp} = +10 sec (310 sec)	37,157 ↑	68.1 –	99 ↑
NESC-1	3rd stage I_{sp} = -10 sec (290 sec)	37,109 ↓	68.1 –	51 ↓
NESC-1	1st stage PMF = +0.02 (0.8573)	36,586 ↓	68.1 –	91 ↑
NESC-1	1st stage PMF = -0.02 (0.8171)	37,707 ↑	68.1 –	59 ↓
NESC-1	2nd stage PMF = +0.02 (0.8480)	36,909 ↓	68.1 –	123 ↑
NESC-1	2nd stage PMF = -0.02 (0.8078)	37,375 ↑	68.1 –	32 ↓
NESC-1	3rd stage PMF = +0.02 (0.7308)	37,134 ↑	68.1 –	114 ↑
NESC-1	3rd stage PMF = -0.02 (0.6908)	37,133 –	68.1 –	34 ↓
NESC-4A	Baseline ground rules and assumptions	37,187 –	68.9 –	142 –
NESC-4A	1st stage I_{sp} = +10 sec (310 sec)	37,205 ↑	68.9 –	162 ↑
NESC-4A	1st stage I_{sp} = -10 sec (290 sec)	37,170 ↓	68.9 –	125 ↓
NESC-4A	2nd stage I_{sp} = +10 sec (310 sec)	37,217 ↑	68.9 –	172 ↑
NESC-4A	2nd stage I_{sp} = -10 sec (290 sec)	37,159 ↓	68.9 –	114 ↓
NESC-4A	3rd stage I_{sp} = +10 sec (370 sec)	37,209 ↑	68.9 –	163 ↑
NESC-4A	3rd stage I_{sp} = -10 sec (350 sec)	37,166 ↓	68.9 –	121 ↓

NESC 4 Sensitivity Study Summary (cont.)

■ = parent vehicle

↓ / ↑ = with reference to parent vehicle

Group	Sensitivity Study	GLOM (lb_m)	Veh. Length (ft)	Payload (lb_m)
NESC-4A	1st stage PMF = +0.02 (0.8573)	36,644 ↓	68.9 –	161 ↑
NESC-4A	1st stage PMF = -0.02 (0.8171)	37,758 ↑	68.9 –	124 ↓
NESC-4A	2nd stage PMF = +0.02 (0.8494)	36,971 ↓	68.9 –	195 ↑
NESC-4A	2nd stage PMF = -0.02 (0.8093)	37,421 ↑	68.9 –	94 ↓
NESC-4A	3rd stage PMF = +0.02 (0.6897)	37,188 ↑	68.9 –	184 ↑
NESC-4A	3rd stage PMF = -0.02 (0.6497)	37,187 –	68.9 –	99 ↓
NESC-4B	160 nmi circular orbit altitude	37,223 ↑	68.9 –	177 ↑
NESC-4C	120 nmi circular orbit altitude	37,252 ↑	68.9 –	206 ↑
NESC-4D	1st and 2nd stage pump-fed propulsion systems	36,196 ↓	66.4 ↓	333 ↑
NESC-4E	Vehicle structural safety factor = 1.2	36,189 ↓	66.4 –	336 ↑
NESC-4F	50% MGA allowable (12.5% batt, avionics; 9% all other)	35,907 ↓	66.4 –	404 ↑
NESC-4G	25% MGA allowable (6.25% batt, avionics; 4.5% all other)	35,764 ↓	66.4 –	441 ↑
NESC-4H	1st and 2nd stage LOX / RP-1 MR = 2.50	35,918 ↑	67.1 ↑	402 ↓
NESC-4i	1st stage propellant reduction for burnout at max Q +10 sec	25,966 ↓	56.0 ↓	182 ↓
NESC-4J	2nd stage propellant reduction targeting 140 lb_m payload	22,436 ↓	53.3 ↓	142 ↓
NESC-4J	2nd stage thrust = +4,000 lb_f (22 klb_f)	23,516 ↑	53.3 –	137 ↓
NESC-4J	2nd stage thrust = +8,000 lb_f (26 klb_f)	23,585 ↑	53.3 –	129 ↓
NESC-4J	2nd stage thrust = +12,000 lb_f (30 klb_f)	23,651 ↑	53.3 –	119 ↓
NESC-4J	1st stage thrust = +5,000 lb_f (60 klb_f)	23,470 ↑	53.3 –	142 –
NESC-4J	1st stage thrust = +10,000 lb_f (65 klb_f)	23,504 ↑	53.3 –	140 ↓
NESC-4J	1st stage thrust = +15,000 lb_f (70 klb_f)	23,538 ↑	53.3 –	136 ↓



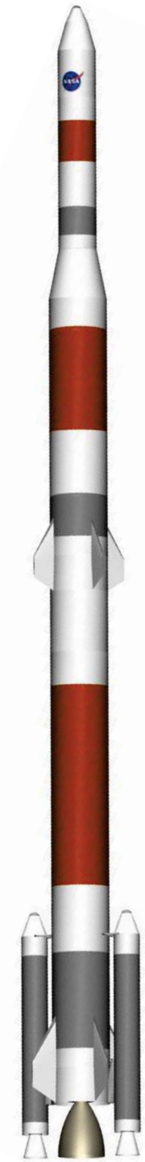
NESC-4Q

NESC 4 Sensitivity Study Summary (cont.)

■ = parent vehicle

↓ / ↑ = with reference to parent vehicle

Group	Sensitivity Study	GLOM (lb_m)		Veh. Length (ft)		Payload (lb_m)	
NESC-4K	2nd stage RP-1 tank dome-to-dome, propellant moved to 3rd stage	23,352	↑	57.2	↑	81	↓
NESC-4L	3rd stage propellant load (and payload) optimization	22,675	↓	53.6	↓	134	↑
NESC-4N	MERs scrubbed and model rebaslined	22,672	↓	52.3	↓	116	↓
NESC-4N	1st and 2nd stage vehicle diameter = -0.17 ft (4.0 ft)	22,647	↓	54.4	↑	125	↑
NESC-4N	1st and 2nd stage vehicle diameter = -0.32 ft (3.85 ft)	22,634	↓	56.1	↑	134	↑
NESC-4N	1st and 2nd stage vehicle diameter = -0.87 ft (3.30 ft)	22,656	↓	65.6	↑	156	↑
NESC-4o	2nd stage thrust = -2,000 lb_f (16 klb_f)	22,614	↓	65.6	–	154	↓
NESC-4o	2nd stage thrust = -4,000 lb_f (14 klb_f)	22,562	↓	65.6	–	148	↓
NESC-4o	2nd stage thrust = +2,000 lb_f (20 klb_f)	22,703	↑	65.6	–	154	↓
NESC-4P	3rd stage thrust = +200 lb_f (1.2 klb_f)	22,674	↑	65.6	–	159	↑
NESC-4Q	+2 SRBs, 1st/2nd stage passive guidance systems, rail launch	27,417	↑	67.8	↑	190	↑
NESC-4Q.2	+2 SRBs, 1st/2nd stage active guidance systems, tower launch	26,718	↑	64.1	↓	63	↓
NESC-4R	+4 SRBs, 1st/2nd stage passive guidance systems, rail launch	32,169	↑	68.3	↑	235	↑
NESC-4R.2	+4 SRBs, 1st/2nd stage active guidance systems, tower launch	31,275	↑	64.9	↓	72	↓
NESC-4S	Original scarring of NESC-4Q.2	22,675	↓	67.8	↑	140	↑
NESC-4T	100 lb_m payload target	22,378	↓	58.0	↓	98	↓



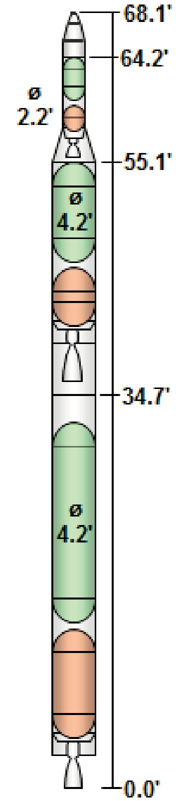
NESC-4Q

NESC-1 (baseline)

Interstage	Second/Third
Dry Mass	33 lbm

Third Stage	
Propellants	LOX / Jet-A
Nominal Ascent Propellant	1,012 lbm
Stage pmf	0.7108
Dry Mass	360 lbm
Burnout Mass	412 lbm
# Engines	1
Engine Thrust (100.0%)	1,000 lbf @ Vac
Engine Isp (100.0%)	300.0 sec @ Vac
Stage Burn Time	303.9 sec

Delivery Orbit	
LEO Delivery	200.0 x 200.0 nmi @ 28.5°
LEO Gross Payload	75 lbm (34.0 kg)
Insertion Altitude	200.0 nmi
T/W @ Liftoff	1.37
Max Dynamic Pressure	714 psf
Max g's Ascent Burn	5.14
T/W @ 2nd Stage Ignition	1.34
T/W @ 3rd Stage Ignition	0.67



GLOM	**37,133 lbm**
Shroud Jettison Mass	47 lbm

First Stage	
Propellants	LOX / Jet-A
Total Stage Ascent Propellant	20,133 lbm
Stage pmf	0.8372
Dry Mass	3,448 lbm
Burnout Mass	3,915 lbm
# Engines	1
Engine Thrust (100.0%)	55,000 lbf @ Vac
Engine Isp (100.0%)	300.0 sec @ Vac
Mission Power Level	100.0%
Stage Burn Time	109.8 sec

Interstage	First/Second
Dry Mass	52 lbm

Second Stage	
Propellants	LOX / Jet-A
Nominal Ascent Propellant	9,482 lbm
Stage pmf	0.8279
Dry Mass	1,720 lbm
Burnout Mass	1,971 lbm
# Engines	1
Engine Thrust (100.0%)	18,000 lbf @ Vac
Engine Isp (100.0%)	300.0 sec @ Vac
Stage Burn Time	158.0 sec

20 SEP 2012

JBH / ED04

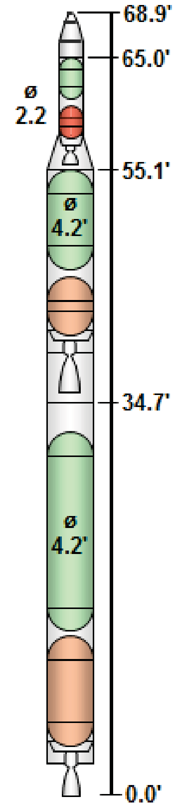
NESC-1

NESC-4A (baseline)

Interstage	Second/Third
Dry Mass	35 lbm

Third Stage	
Propellants	LOX / LCH4
Nominal Ascent Propellant	957 lbm
Stage pmf	0.6697
Dry Mass	420 lbm
Burnout Mass	472 lbm
# Engines	1
Engine Thrust (100.0%)	1,000 lbf @ Vac
Engine Isp (100.0%)	360.0 sec @ Vac
Stage Burn Time	344.5 sec

Delivery Orbit	
LEO Delivery	200.0 x 200.0 nmi @ 28.5°
LEO Gross Payload	142 lbm (64.5 kg)
Insertion Altitude	200.0 nmi
T/W @ Liftoff	1.36
Max Dynamic Pressure	717 psf
Max g's Ascent Burn	5.06
T/W @ 2nd Stage Ignition	1.33
T/W @ 3rd Stage Ignition	0.64



GLOM	37,187 lbm
Shroud Jettison Mass	48 lbm

First Stage	
Propellants	LOX / Jet-A
Nominal Ascent Propellant	20,133 lbm
Stage pmf	0.8372
Dry Mass	3,448 lbm
Burnout Mass	3,916 lbm
# Engines	1
Engine Thrust (100.0%)	55,000 lbf @ Vac
Engine Isp (100.0%)	300.0 sec @ Vac
Mission Power Level	100.0%
Stage Burn Time	109.8 sec

Interstage	First/Second
Dry Mass	52 lbm

Second Stage	
Propellants	LOX / Jet-A
Nominal Ascent Propellant	9,482 lbm
Stage pmf	0.8293
Dry Mass	1,700 lbm
Burnout Mass	1,952 lbm
# Engines	1
Engine Thrust (100.0%)	18,000 lbf @ Vac
Engine Isp (100.0%)	300.0 sec @ Vac
Stage Burn Time	158.0 sec

16 OCT 2012

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NESC-4A

NESC-4T (100 lb_m target)

Third Stage	
Propellants	LOX / LCH4
Nominal Ascent Propellant	1,227 lbm
Stage pmf	0.6986
Dry Mass	447 lbm
Burnout Mass	529 lbm
# Engines	1
Engine Thrust (100.0%)	1,200 lbf @ Vac
Engine Isp (100.0%)	360.0 sec @ Vac
Stage Burn Time	368.0 sec

Solid Booster (each)	Mk 70 Mod 1 ER
Casing Type	Expendable
Propellants	HTPB
Overboard Propellant	2,986 lbm
Stage pmf	0.7042
Burnout mass	1,274 lbm
# Boosters	2
Average Thrust @ 70 °F	62,800 lbf
Stage Burn Time	6.05 sec

Delivery Orbit	
LEO Delivery	120.0 x 120.0 nmi @ 28.5°
LEO Gross Payload	98 lbm (44.5 kg)
Insertion Altitude	120.0 nmi
T/W @ Liftoff	1.85
Max Dynamic Pressure	2,120 psf
Max g's Ascent Burn	8.68
T/W after SRB separation	1.91
T/W @ 2nd Stage Ignition	1.67
T/W @ 3rd Stage Ignition	0.62

18 DEC 2012

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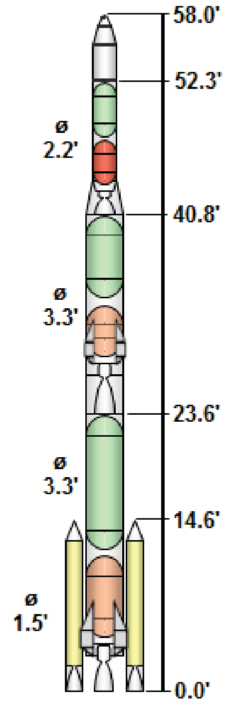

GLOM	22,378 lbm
Shroud Jettison Mass	88 lbm

First Stage	
Propellants	LOX / Jet-A
Nominal Ascent Propellant	8,060 lbm
Stage pmf	0.7953
Dry Mass	1,935 lbm
Burnout Mass	2,075 lbm
# Engines	1
Engine Thrust (100.0%)	45,700 lbf @ Vac
Engine Isp (100.0%)	300.0 sec @ Vac
Mission Power Level	100.0%
Stage Burn Time	52.9 sec

Interstage	First/Second
Dry Mass	43 lbm

Second Stage	
Propellants	LOX / Jet-A
Nominal Ascent Propellant	4,916 lbm
Stage pmf	0.8238
Dry Mass	959 lbm
Burnout Mass	1,051 lbm
# Engines	1
Engine Thrust (100.0%)	14,350 lbf @ Vac
Engine Isp (100.0%)	300.0 sec @ Vac
Stage Burn Time	102.8 sec

Interstage	Second/Third
Dry Mass	29 lbm

NESC-4T